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Hazard assessment of selenium to endangered razorback suckers (*Xyrauchen texanus*)

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Abstract

A hazard assessment was conducted based on information derived from two reproduction studies conducted with endangered razorback suckers (*Xyrauchen texanus*) at three sites near Grand Junction, CO, USA. Selenium contamination of the upper and lower Colorado River basin has been documented in water, sediment, and biota in studies by US Department of the Interior agencies and academia. Concern has been raised that this selenium contamination may be adversely affecting endangered fish in the upper Colorado River basin. The reproduction studies with razorback suckers revealed that adults readily accumulated selenium in various tissues including eggs, and that 4.6 μg/g of selenium in food organisms caused increased mortality of larvae. The selenium hazard assessment protocol resulted in a moderate hazard at the Horsethief site and high hazards at the Adobe Creek and North Pond sites. The selenium hazard assessment was considered conservative because an on-site toxicity test with razorback sucker larvae using 4.6 μg/g selenium in zooplankton caused nearly complete mortality, in spite of the moderate hazard at Horsethief. Using the margin of uncertainty ratio also suggested a high hazard for effects on razorback suckers from selenium exposure. Both assessment approaches suggested that selenium in the upper Colorado River basin adversely affects the reproductive success of razorback suckers.

Keywords: Selenium; Hazard assessment; Razorback sucker; Colorado River; Endangered fish

1. Introduction

Selenium contamination in the upper and lower Colorado River basins has been documented in water, sediment, and biota, in studies by the US Department of the Interior agencies and academia (reviewed in Hamilton, 1998). Historic selenium contamination of the Colorado River basin prior to the construction of mainstream dams has been hypothesized to have contributed to the decline of native fish that are currently federally listed as endangered (Hamilton, 1999). Other reports have suggested that endangered fish, especially razorback suckers (*Xyrauchen texanus*), are being adversely affected by selenium contamination in

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the Green, Price, Yampa, and upper Colorado rivers (Hamilton, 1998; Stephens and Waddell, 1998; Hamilton et al., 2000).

The upper Colorado River provides critical habitats for four endangered fish species, Colorado pikeminnow (*Ptychocheilus lucius*), razorback sucker, humpback chub (*Gila cypha*), and bonytail (*Gila elegans*) (USFWS, 1987; USDOI, 1994). A combined approach for the recovery of the four endangered fish in the upper Colorado River basin has been undertaken in 1987 by the Upper Colorado River Endangered Fish Recovery Program (USFWS, 1987). The goal of the 15-year program is to reestablish self-sustaining populations of the four species while allowing continued water development.

In an effort to stabilize and enhance populations of razorback suckers and other endangered fishes in the upper Colorado River, the Floodplain Habitat Restoration Program within the Recovery Program, has undertaken the task to restore floodplain habitats for use by razorback sucker larvae and adults. The proposed strategy for achieving these goals was to reconnect selected floodplain habitats to the main river channel in a manner that simulated historic hydrological conditions. An important component of this Program was to select sites, which after restoration would not pose contaminant problems to the fish, especially from selenium.

The remaining population of razorback suckers in the middle Green River basin in Utah has been estimated, using similar datasets, at approximately 1000 individuals in 1988 (Lanigan and Tyus, 1989) and at 300–600 in 1992 (Modde et al., 1996). Razorback suckers are rare in the upper Colorado River, where only 10 fish were found in the river between 1989 and 1996 (C. McAda, USFWS, personal communication).

The current hazard assessment used information from two reproduction studies with razorback suckers (Hamilton et al., 2001a,b). The studies evaluated the effects of selenium on adults exposed to water, sediment, and food organisms at three sites in aquatic locations in their current range in the upper Colorado River. Using the species of concern, similar conditions such as water quality, temperature, photoperiod, and relevant biological endpoints that can be linked to population level effects enhanced the realism of the studies (Kenaga, 1982).

Extrapolating the results of the two reproduction studies to the potential hazard in the field is a practical need in implementing the actions necessary to the recovery of endangered razorback sucker. Although single species testing has been questioned when used to evaluate the hazard to a community or ecosystem (Cairns, 1983), this approach is appropriate when assessing the hazard of selenium in its various forms and combined with other inorganic elements from a source (i.e. irrigation activities) to specific organisms of concern (i.e. federally-listed endangered fishes). Razorback suckers were tested because they were endangered and indigenous to the upper Colorado River basin, not because they were considered the 'most sensitive' species, which is the goal of most toxicity testing (Cairns, 1986).

2. Data source

Two field studies were undertaken to determine the effects of selenium and other inorganic elements on the reproductive success of razorback suckers (Hamilton et al., 2001a,b). These studies were conducted at three sites near Grand Junction, CO, USA, in the general area where razorback suckers have historically been observed. The three sites were the North Pond site at Walter Walker State Wildlife Area (assumed to have elevated selenium contamination), a dyked area of a tertiary channel termed the Adobe Creek site (assumed to have a moderate amount of selenium contamination), and the Horsethief site at Horsethief Canyon State Wildlife Area, which were hatchery ponds used for endangered fish propagation purposes (reference site assumed to have little or no selenium contamination) (Fig. 1). The Horsethief site was located approximately 19 km west of the Grand Junction city limits, the Adobe Creek site was located approximately 5 km west, and the North Pond site was located approximately 0.5 km to the southwest. Although wild fish are free to move about the Colorado River and its tributaries, which may vary their exposure to various stresses, the adults in the two reproduction studies were held in specific locations as part of the exposure.

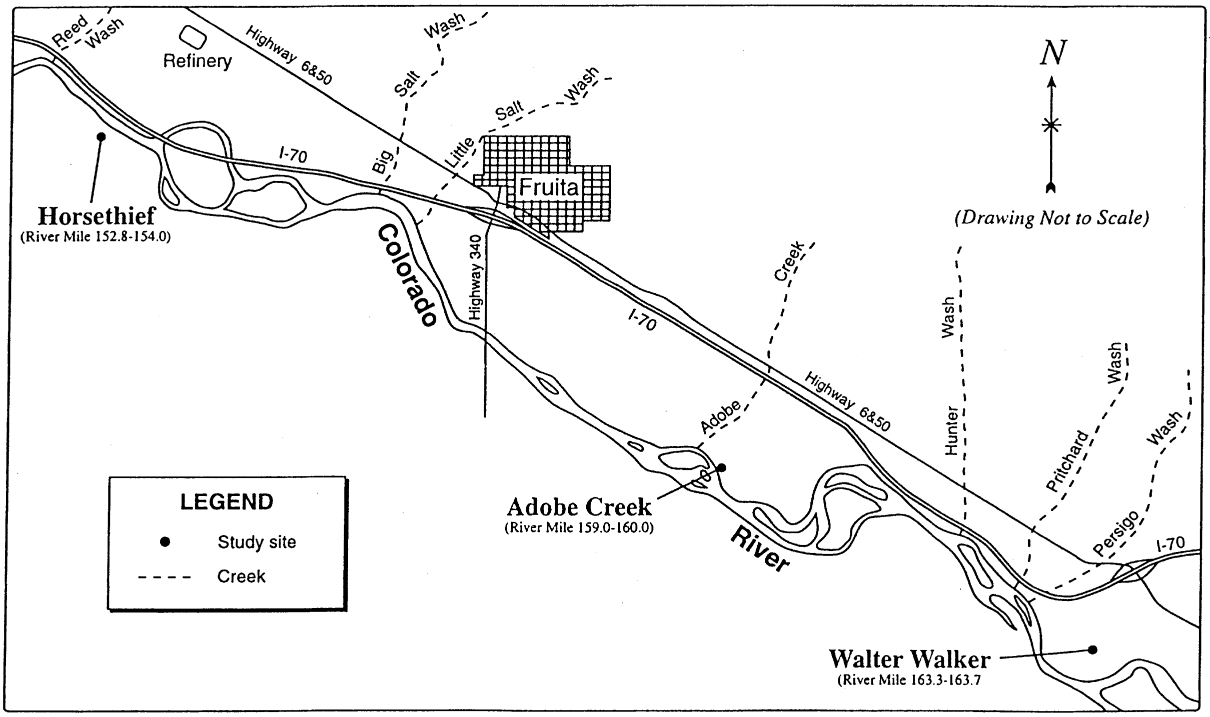

Fig. 1. Map of three sites located in the Grand Valley near Grand Junction, CO, USA, used for two reproduction studies with endangered razorback suckers.

After 9 months exposure in 1995–1996, adults were hand spawned in late spring when water temperatures reached a level associated with naturally spawning of razorback suckers (Hamilton et al., 2001a). Following spawning, tests were conducted with eggs and larvae. The study was repeated in 1996–1997 (Hamilton et al., 2001b).

During the exposure periods, selenium and other inorganic elements was measured on a monthly or semi-monthly basis in water, sediment, zooplankton, and fish eggs at three sites where fish were held. The results of those studies are used here to assess the hazard of selenium to razorback suckers.

In the two reproduction studies, several inorganic elements were measured in water, zooplankton and fish eggs (e.g. aluminum, antimony, arsenic, boron, barium, beryllium, bismuth, cadmium, chromium, cobalt, copper, iron, lead, lithium, magnesium, manganese, molybdenum, nickel, silicon, silver, strontium, thallium, tin, titanium, vanadium, zinc), but only selenium was elevated to concentrations reported to cause adverse effects in fish (Hamilton et al., 2001a,b). This scenario has occurred in other contaminant investigations. For example, Sorensen (1988) stated that 'Fish kills (at Belews Lake, NC, and Martin Lake, TX) were considered a direct result of selenium release into the main basin of the lakes because several hundred analyses for metals, metalloids, physiochemical parameters, and pesticides provided essentially negative results except for sufficiently high levels of selenium in the water (approximately 5 μg/l) to warrant concern.' Lemly (1985) reviewed information in 10 studies of potential causes for the cause of fishery problems at Belews Lake (16 species eliminated, two species present as adults only, one species re-colonized, and one species unaffected), and of the 16 inorganic elements of concern, only selenium was present at elevated concentrations in water and fish. Saiki and Lowe (1987) measured several inorganic and organic chemicals in water and biota collected from Kesterson Reservoir area, CA, and concluded that only selenium was elevated sufficiently to be of concern to fisheries resources. Nakamoto and Hassler (1992) measured 20 trace elements in fish from the Merced River and Salt Slough, San Joaquin Valley, CA, which was primarily from irrigation return flows and concluded only selenium was present at toxic concentrations. Gillespie and Baumann (1986) concluded that selenium was the element causing the deformities and reduced survival of bluegill larvae and not other elements (arsenic, cadmium, copper, lead, mercury, zinc) present in females from Hyco Reservoir, NC. Bryson et al. (1984) concluded that selenium was the only element elevated sufficiently in zooplankton collected from Hyco Reservoir, NC, and not other elements (arsenic, cadmium, copper, mercury, or zinc) to cause the 97% mortality of juvenile bluegill after 1 week of dietary exposure. Montgomery Watson (1998) concluded that selenium was the major element of concern associated with phosphate mining activities in the Blackfoot River watershed of southeastern Idaho and not other elements (cadmium, manganese, nickel, vanadium, and zinc). Skorupa (1998) reviewed 12 environmental case studies of clearly confirmed or highly probable selenium poisoning in nature, even though other inorganic elements were present.

3. Hazard assessment protocol

Lemly (1995) presented a protocol for aquatic hazard assessment of selenium, which was formulated primarily in terms of the potential for food-chain bioaccumulation and reproductive impairment in fish and aquatic birds. The protocol incorporated five ecosystem components including water, sediment, benthic invertebrates, fish eggs and bird eggs. Each component was given a numeric score based on the degree of hazard: 1, no identifiable hazard; 2, minimal hazard; 3, low hazard; 4, moderate hazard; and 5, high hazard. The final hazard characterization was determined by adding the individual scores and comparing the total to the following evaluation criteria: 5, no hazard; 6–8, minimal hazard; 9–11, low hazard; 12–15, moderate hazard; and 16–25, high hazard. Lemly (1996a) modified his protocol for use with four ecosystem components due to the difficulty in collecting residue information for all five components in an assessment. He adjusted the final ecosystem-level hazard assessment to the following four-component evaluation criteria: 4, no hazard; 5–7, minimal hazard; 8–10, low hazard; 11–14, moderate hazard; and 15–20, high hazard.

Lemly (1995) defined five categories of hazards as follows: (1) high hazard denotes an imminent, persistent toxic threat sufficient to cause complete reproductive failure in most species of fish and aquatic birds; (2) moderate hazard indicates a persistent toxic threat of sufficient magnitude to substantially impair but not eliminate reproductive success; some species will be severely affected whereas others will be relatively unaffected; (3) low hazard denotes a periodic or ephemeral toxic threat that could marginally affect the reproductive success of some sensitive species, but most species will be unaffected; (4) minimal hazard indicates that no toxic threat is identified but concentrations of selenium are slightly elevated in one or more ecosystem components (water, sediment, invertebrates, fish eggs, bird eggs) compared to uncontaminated reference sites; (5) no hazard denotes that no toxic threat is identified and selenium concentrations are not elevated in any ecosystem component. Table 1 gives the hazard terms and corresponding selenium concentration range for each of the ecosystem components in the four-component model (Lemly, 1996a).

These protocols have been used to assess the selenium hazard to aquatic ecosystems at Ouray NWR, UT, the Animas, LaPlata, and Mancos rivers in the San Juan River basin, and three Wildlife Management Areas in Nevada (Lemly, 1995, 1996a, 1997). Although the original protocol was published in 1995, apparently no critiques have been published pointing out any deficiencies in the protocol (D. Lemly, USFS, personal communication).

4. Hazard assessment

The information from the 1995–1996 reproduction study (Table 2) and the 1996–1997 study (Table 3) were used with the four–component hazard assessment. In both studies, the final haz-

Table 1
Hazard rating table based on Lemly (1996a)

		Hazard and selenium concentration range				
		None	Minimal	Low	Moderate	High
Ecosystem component	Water (μg/l)	<1	1–2	2–3	3–5	>5
	Sediment (μg/g)	<1	1–2	2–3	3–4	>4
	Benthic invertebrate (μg/g)	<2	2–3	3–4	4–5	>5
	Fish eggs (μg/g)	<3	3–5	5–10	10–20	>20

ards were moderate at Horsethief and high at Adobe Creek and North Pond. It is interesting to note that even though sediments at Adobe Creek were ranked as a minimal hazard in the 1995–1996 study and low in the 1996–1997 study, selenium concentrations in water, invertebrates and fish eggs ranked as high hazards. The outcome of the hazard assessment protocol coincides with the observations in the razorback sucker larvae study with larvae fed zooplankton from Adobe Creek and North Pond, but not from Horsethief. There was a sharp increase in mortality during the first week of exposure of razorback sucker larvae-fed zooplankton containing 4.6 μg/g selenium from Horsethief east wetland (HTEW) in both the 1995–1996 and 1996–1997 studies suggested that

Table 2
Hazard assessment of selenium in the razorback sucker reproduction study conducted in 1995–1996

Site and environmental component	Selenium concentration[a]	Evaluation by component		Totals for the site	
		Hazard	Score	Score	Hazard
Horsethief					
Water	<1–3.8	Moderate	4		
Sediment	0.2–1.4	Minimal	2	14	Moderate
Benthic invertebrate	8.0–14	High	5		
Fish egg	5.8–6.8	Low	3		
Adobe Creek					
Water	1.5–12	High	5		
Sediment	0.5–2.1	Minimal	2	17	High
Benthic invertebrate	28–45	High	5		
Fish egg	36–65	High	5		
North Pond					
Water	3.8–20	High	5		
Sediment	7.2–55	High	5	20	High
Benthic invertebrate	11–45	High	5		
Fish egg	34–41	High	5		

[a] Range of selenium concentrations in μg/l for water, μg/g for sediment, benthic invertebrate, and fish eggs.

Table 3
Hazard assessment of selenium in the razorback sucker reproduction study conducted in 1996–1997

Site and environmental component	Selenium concentration[a]	Evaluation by component		Totals for the site	
		Hazard	Score	Score	Hazard
Horsethief					
Water	<1.4–3.0	Moderate	4		
Sediment	0.8–0.9	Minimal	2	14	Moderate
Benthic invertebrate	7.9–9.3	High	5		
Fish egg	5.9–6.7	Low	3		
Adobe Creek					
Water	<0.7–4.5	Moderate	4		
Sediment	1.2–2.5	Low	3	17	High
Benthic invertebrate	32–48	High	5		
Fish egg	36–43	High	5		
North Pond					
Water	3.2–17	High	5		
Sediment	2.9–16	High	5	20	High
Benthic invertebrate[b]	11–45	High	5		
Fish egg	52–60	High	5		

[a] Range of selenium concentrations in μg/l for water, μg/g for sediment, benthic invertebrate, and fish egg.
[b] Data from Hamilton et al. (2001a).

the protocol may be conservative (Hamilton et al., 2001a,b).

It should be noted that the selenium values used in the protocol for water and fish eggs came from the hatchery ponds at Horsethief and selenium values in sediment and benthic invertebrates were from HTEW, whereas the zooplankton used in the larval fish study came from HTEW, which received effluent only from the hatchery ponds. The sediments in Horsethief east wetland seemed to be rich in organic material, and thus probably contain a large reservoir of selenium available to the wetland ecosystem even though the top layer of sediment had 0.8–0.9 μg/g selenium. These incongruities, [i.e. (1) the use of zooplankton in the larval fish test; and (2) use of water, sediment, benthic invertebrates, and fish egg values from the hatchery pond source] may have caused the hazard estimate from the protocol to be lower than the actual outcome of the toxicity test with razorback sucker larvae.

The protocol specifies benthic invertebrates, but not water-column invertebrates such as zooplankton, be used as the dietary component of the protocol. The proposed dietary threshold for adverse effects from selenium in sensitive aquatic organisms was 3 μg/g (Maier and Knight, 1994; Lemly, 1996b), but the dietary source or type, i.e. water-column organisms, benthic organisms, plant material, detritus, or prepared diet, was not specified. It seems reasonable that if the dietary toxic threshold is 3 μg/g, then in the protocol, the high hazard should be associated with a value closer to 3 μg/g rather than >5 μg/g.

5. Quotient method

Comparing the biological effects concentration (BEC) with the expected (or measured) environmental concentrations (EEC) is a basic principle in evaluating the hazard of toxicants to aquatic life (Kimerle et al., 1979). The BEC/EEC quotient has been referred to as the margin of uncertainty. In the early stages of hazard evaluation (i.e. acute toxicity tests) neither the BEC nor EEC is a precise value, but rather are values with wide confidence intervals due to variability associated with the BEC and EEC (Mount, 1981). For example, the BEC will vary with the species and life stage tested, organism health, genetic constitution, route of exposure, water quality and acclimation. The EEC will vary depending on water quality of the receiving water, mixing characteristics (flow rate, input rate, etc.), degradation (photo, biological, or chemical), and seasonal changes. Many of these concerns were specifically addressed in the experimental design of the present study, thus removing a substantial amount of uncertainty in the BEC and EEC values.

To evaluate the hazard of selenium in the present study, the margin of uncertainty was calculated by comparing the BEC (4.6 $\mu g/g$ dietary selenium concentration causing adverse effects in razorback sucker larvae) with the EEC measured in potential food organisms of razorback sucker larvae collected from various aquatic locations in the upper Colorado River basin including the Green River. Margins of uncertainty of one [BEC/EEC=1] using field study-derived data indicate a high potential for environmental hazard, whereas higher margins (i.e. >1) indicate low potential (OECD, 1989). Other examples of uncertainty factors include 10 for good quality chronic toxicity data, 100 for limited or poor chronic data, and 1000 for no chronic data (OECD, 1989). The US Environmental Protection Agency recommends similar safety factors (USEPA, 1984), and there is international, national, and federal support of uncertainty (safety) factors in hazard assessments (Dourson and Stara, 1983).

Several studies have reported selenium concentrations >4.6 $\mu g/g$ in aquatic invertebrates in aquatic habitats in the upper Colorado River basin (Barnhart, 1957; Birkner, 1978; Butler et al., 1991, 1994, 1996; Peltz and Waddell, 1991; Stephens et al., 1992; Waddell and Wiens, 1994; Hamilton et al., 1996; Wiens and Waddell, 1996), and other reports have reported selenium concentrations in aquatic invertebrates greater than the dietary selenium threshold of 3 $\mu g/g$ (Osmundson, 1989, 1992). Consequently, the BEC/EEC ratio would be less than one for several locations in the upper Colorado River basin, which suggests that adverse effects on razorback sucker recruitment are probably occurring.

6. Selenium is a concern in the Colorado River basin

Following the discovery of selenium-contaminated irrigation return waters in the San Joaquin Valley of central California in 1982, the Department of the Interior (DOI) initiated the National Irrigation Water Quality Program (NIWQP) to identify other areas in the western US that have water quality problems induced by irrigation drainage (Feltz et al., 1991). The NIWQP investigations focused on irrigation drainage facilities constructed by the DOI where the drainwater was to a national wildlife refuge, or had the potential to impact migratory birds or endangered species. The upper Colorado River basin, including the middle Green River basin of Utah and the upper Colorado, Gunnison, and Uncompahgre rivers in northwestern Colorado were identified as areas needing further study. Analysis of water, bottom sediments and biota collected since 1986 from the middle Green River basin and the Grand Valley, located in western Colorado and includes a portion of the Colorado, Gunnison and Uncompahgre rivers, have confirmed the presence of inorganic elements including selenium at concentrations that could be potentially harmful to fish and wildlife (Butler et al., 1989, 1991, 1994, 1996; Stephens et al., 1988, 1992; Peltz and Waddell, 1991).

The NIWQP studies provided a basic foundation of survey information on the occurrence of selenium in fish collected from a variety of aquatic ecosystem components that suggested selenium and possibly other contaminants might be sufficiently elevated to be contributing to the decline of endangered fish. Selenium in soils of the western states is derived from weathering of outcrops of Cretaceous marine rocks in the Rocky Mountain and Great Plains regions, which comprises an area of approximately 300 000 square miles (Presser et al., 1994).

The US Fish and Wildlife Services' National Contaminant Biomonitoring Program (NCBP) has documented elevated selenium concentrations in fish collected from stations located in the upper and lower Colorado River basins. The NCBP monitors temporal and spatial trends in concentrations of persistent environmental contaminants, including selenium, that may threaten fish and wildlife. Of 98–112 nationwide stations where fish were collected every other year between 1972 and 1984, selenium concentrations in fish from approximately 11–16 stations have exceeded the 85th percentile, which was selected arbitrarily as a point distinguishing 'high' concentrations (May and McKinney, 1981). Selenium concentrations in whole-body fish from the Colorado River basin have been among the highest in the nation (Walsh et al., 1977; Lowe et al., 1985; Schmitt and Brumbaugh, 1990). In samples collected in 1972–1973, selenium concentrations exceeded the 85th percentile in fish at five of six stations in the Colorado River basin: Green River at Vernal, UT (the only upper basin station) and Colorado River at four sites in Arizona (Imperial Reservoir, Lake Havasu, Lake Mead, and Lake Powell). In 1978–1981 and 1984, selenium concentrations exceeded the 85th percentile at six of seven stations; the five above plus the Colorado River at Yuma, AZ. The only station at which selenium concentrations in fish have not exceeded the 85th percentile was on the Gila River (San Carlos Reservoir, AZ).

Prior to the NIWQP and NCBP studies, studies in the 1930s by the US Department of Agriculture reported elevated selenium concentrations in water in the upper and lower Colorado, Gunnison and San Juan rivers due to irrigation activities (Anderson et al., 1961). Elevated selenium concentrations in water 48 and 112 km southeast of the mouth of the Colorado River in the Gulf of California were also reported. The long-term contamination of the lower Colorado River basin may have been one of the factors contributing to the disappearance of endangered fish in the early 1930s as reported by Dill (1944). More recently, elevated selenium concentrations in water, sediment, and biota in the lower Colorado River basin documented in a NIWQP study were identified as coming from the upper basin (Radtke et al., 1988; Radtke and Kepner, 1990).

Widespread selenium contamination of the Colorado River basin has been reported. In the upper basin, Stephens and Waddell (1998) reviewed several NIWQP investigations, data in the National Water Data Storage and Retrieval System of the USGS, Floodplain Habitat Restoration Program, and contaminant assessment reports of the USFWS, and reported that selenium was present at concentrations harmful to fish and wildlife at several locations in the Green River basin including Ashley Creek, Anderson Bottom in the Canyonlands area, Desert Lake Waterfowl Management Area, Escalante Ranch, Sheppard Bottom in Ouray NWR, Stewart Lake, Pariette Wetlands, and the Price and Yampa rivers. Bussey et al. (1976) measured 10 inorganic elements in various fish tissues collected from Lake Powell and concluded that only selenium was elevated to concentrations of concern from a human consumption standpoint. In muscle tissue, selenium concentrations were 12.2 μg/g in largemouth bass (*Micropterus salmoides*) and 16.8 μg/g in black crappie (*Pomoxis nigromaculatus*), which were higher than the proposed toxic threshold (8 μg/g) for adverse effects in fish (Lemly, 1996b), whereas they were 6.4 μg/g in walleye (*Stizostedion vitreum*).

Hamilton (1998) reviewed similar sources plus university studies primarily from the lower Colorado River basin and reported selenium contamination throughout the upper and lower Colorado River basin. He concluded that selenium concentrations were sufficiently elevated to be causing reproductive problems in endangered fish such as the razorback sucker. In a follow-up paper, he reviewed historical data on selenium concentrations in the upper and lower basins, along with historical records and reviews of the occurrence of native, later endangered fish, and presented a hypothesis that suggested selenium contamination from irrigated agriculture in the 1890–1910 period caused the decline of native fish in the upper basin in the 1910–1920 period and in the lower basin in the 1925–1935 period (Hamilton, 1999).

7. Conclusions

Assessing the hazard of selenium to razorback suckers using either the selenium hazard assessment protocol or the BEC/EEC ratio suggested that selenium is probably adversely affecting the reproductive success of razorback sucker. Other reports have suggested adverse effects from selenium were occurring in aquatic organisms in the Colorado River basin. Based on selenium concentrations measured in water, sediment, aquatic invertebrates and fish given in published NIWQP reports of studies in the Green River and upper Colorado River basins, and biological effects measured in the two reproduction studies (Hamilton et al., 2001a,b), selenium contamination is probably adversely affecting razorback sucker. The recovery of razorback suckers should include addressing selenium contamination issues in the upper Colorado River basin, in addition to ongoing efforts to address other factors contributing to the decline of endangered fish in the upper Colorado River basin such as stream alteration (dams, irrigation withdrawals, dewatering, channelization), loss of habitat (spawning sites, and backwater nursery areas), changes in flow regime, blockage of migration routes, water temperature and clarity changes, competition with and predation by introduced species, parasitism, and changes in food base (USFWS, 1987).

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